Texture Models for High-Resolution Ocean Microwave Imagery

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***Abstract* - Computer simulations of ocean passive microwave images and texture features are developed in the context with high-resolution radiometric observations. The technique is based on statistical and deterministic characterizations of spatial-variable fields (image scenes) containing ensembles of different radio-hydro-physical factors – surface roughness, foam, whitecap, spray, and bubbles. The corresponding microwave contributions are calculated using available hydrodynamic-electromagnetic models. In particular, we employ the well known resonance model for simulations of low-contrast signatures (~ 2 - 3 K) due to ocean surface roughness and macroscopic dielectric models for simulations of high-contrast signatures (~ 10 - 20 K) induced by foam/whitecap. Spatial and statistical combinations of these factors including the generation of fractal geometrical sets allow us to model a novel class of ocean microwave textures and distinct radiometric features. Some of them have been observed and analyzed during remote sensing experiments conducted by NOAA/ETL. Examples of the texture modeling and synthesis are presented and discussed in the paper.**

I. INTRIDUCTION

High-resolution multi-band passive microwave imagery provides detailed observations of ocean variables [1,2,3]. Under certain atmospheric conditions, the multi-band images obtained indicate a spatial nonuniformity of the ocean surface through variations of the thermal microwave radiance. The most abundant phenomena such as surface roughness change, wave breaking, and foam/whitecap activity become accessible for systematic microwave monitoring and precise mapping. Two important problems have arisen in this connection: 1) selection and evaluation of the relevant 2-D radiometric information and so-called "signatures of interest," and 2) their geophysical validation and interpretation. We develop both tasks through the combined methods of digital image processing and texture modeling. This option allows us to investigate comprehensively multi-band ocean microwave imagery providing *scene matching* and *detection*. These procedures are based on image segmentations and a link between model and experimental image data. As a result, variations of the ocean parameters can be verified by selected texture features.

II. TEXTURE CHARACTERIZATION

Texture information plays an important role in remote sensing and image analysis. Texture increases the realism of the produced pictures and represents spatial properties of the images. Three principal methods are applied for descriptions of texture: 1) structural, 2) stochastic, and 3) spectral. Structural techniques characterize textures as an arrangement of pixels, objects, or (sub)patterns according to certain placement laws. Stochastic techniques provide global characterization of texture as a random field of variables. The statistical properties of an image are determined, e.g., by the probability density function (pdf). Spectral techniques describe the periodicity of texture and operate with properties of the 2-D Fourier spectrum.

Analyses of the collected radiometric databases [4,5] have shown that high-resolution (~ 1 - 3 km) ocean microwave images comprise all three type of textures, depending on the situation. Stochastic radio-brightness textures occur due to environmental ocean dynamics; they present the so-called "stochastic microwave image background." These textures are simulated perfectly using random field models [6,7]. At the same time, distinct radio-brightness textures and objects – spots of different contrast and shape, can be generated using deterministic 2-D hydrodynamic theories (e.g., [8]). Low-contrast spot-type features are observed in the experimental ocean microwave images as well. Finally, periodic microwave textures may appear in the images as a result of spatial modulations of surface roughness induced, for instance, by oceanic internal waves or atmospheric convection cells. Adequate radio-brightness textures can be simulated using the Fourier methods and modulational hydrodynamic functions.

Eventually, the most realistic image scenes related to the ocean surface can be simulated using combinations of the listed methods. To investigate this problem, we apply direct numerical modeling and texture-fitting algorithms. The decision-making criteria are based on the manifestation of correlations (multi-band and spatial) between model and experimental data. An important interference factor is noise – instrumental and environmental. The additive noise is incorporated into texture-

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fitting algorithms as a constant term, whereas a speckle noise can be removed using filtering operations.

III. PROCEDURE

Many models and computer techniques have been proposed for generations of 2-D and 3-D textures after the pioneer publication of *Rosenfeld & Lipkin*, 1970. Concerning remote sensing, the following texture models can be considered: 1) mosaic – cell and "bombing," 2) periodic, 3) Fourier series, 4) Brownian motion, 5) fractal, and 6) Markov chain. Models 1 and 2 are deterministic, models 3 - 6 are statistical. Although all these models differ in a mathematical sense, the algorithm for texture simulations of oceanic scenes can be formulated using a unified method. It is based on a discrete image representation and quantization of ocean radio brightness. For this, the following consecutive operations are applied (Fig. 1).

1) Generation of a discrete field of large numbers of pixels in a coordinate plane by certain deterministic or statistical laws;

2) Calculations of the pixel intensities, i.e., the values of the brightness temperature (contrast) related to different oceanic factors. For this, well developed ocean microwave emission models and empirical approximations are used;

3) Labeling of the pixels covering a specified image region, pattern, or geometrical figures. This procedure provides a preliminary coding of image features, which could be associated then with the "signatures of interest."

4) Color quantization of the pixels by intensities. This operation arranges the value of the calculated brightness temperature for each pixel in standard RGB color format.

5) Digital interpolation, gridding, and sampling of the image or selected image regions. These procedures provide the transformation of a quantitative discrete field of pixels into a continuous color image of specified size.

During these operations, we can generate the actual microwave image scene $T_B(x,y)$ in terms of the brightness temperature (or contrast). The image will correspond to an original oceanic scene with specified parameters. This algorithm can be applied repeatedly for each microwave channel since the input parameters are dependent on the electromagnetic wave and polarization. Thus, a multi-dimension array, i.e., a multi-spectral formatted image, is formed.

In real situations, however, we have to consider an observation process

$$T_I(x,y) = \int P(x-x', y-y') T_B(x', y') dx'dy' + \Theta(x,y), \qquad (1)$$

where $T_I(x,y)$ is the desired scene, $P(x',y')$ is the spread function describing the gain pattern of the radiometric antenna, and $\Theta(x,y)$ is the additive noise factor. Computations utilizing (1) involve difficulties because it is necessary to know the signal-to-noise characteristics and geometry of the experiment. Preliminary estimations, however, show that in the case of low-contrast ocean scenes (related usually to surface roughness) the observation process (1) doesn't change the resulting microwave textures significantly. In the case of high-contrast objects such as foam/whitecap or bubble patches, ignoring the convolution (1) may introduce large errors and distortions. Although theoretically such "bombing" textures can be observed, in the experimental radiometric images they may disappear due to blurred and noisy effects. In the other words, detectability of texture features depends on the spatial resolution (pixel size) and a space-time averaging process. These factors are taken into account in (1).

Manipulations with different deterministic and statistical texture realizations provide a texture synthesis. Synthesized textures present *macro-textures* with complicated properties. Sometimes, macro-textures are useful for recognition of complex features. Correlations between textures (multi-band and spatial) may occur in the presence of regular objects and/or quasi-periodic structures in the images. Therefore, searching for correlations (decorrelations) between image features is an important task of our texture syntheses.

IV. MICROWAVE CONTRIBUTIONS

As we mentioned above, the properties of microwave textures depend on spatially statistical distributions of radio brightness. First it is necessary to estimate the microwave emission contributions from different factors. For this, the following microwave emission models [9,10,11] can be used:

$$\Delta T_{Bs}(k_0, \theta, \varphi; t, s; V) = 2T_0 k_0^2 \int_{k_{\min}}^{\infty} \int_{-\pi}^{\pi} G(K, k_0; \theta, \varphi - \varphi') S(K, \varphi'; V) K dK d\varphi'$$

– for surface roughness (resonance model), (2)

$$\Delta T_{Bf}(\lambda, \theta; t, s; \vec{q}) = T_0 [R_0(\lambda, \theta; t, s) - R_f(\lambda, \theta; t, s; \vec{q})]$$

– for foam/whitecap/bubbles (macroscopic model), (3)

where the brightness temperature contrast (relatively to a smooth water surface) $\Delta T_{Bs,f}(k_0, \theta, \varphi; t, s; V)$ is a multi-parametric function of a number of key variables: the electromagnetic wavelength λ, incidence and azimuthal angles $\{\theta, \varphi\}$, physical temperature t, salinity s, and wind speed V; $S(K, \varphi'; V)$ is the two-dimensional wave number spectrum of a rough surface $z = \xi(x,y)$; $G(...)$ is the resonance function describing the radiation from a single harmonic surface with the wave number K (this function corresponds to the second-order scattering terms in the small-perturbation expansion [10]); $k_0 = 2\pi/\lambda$ is the electromagnetic wave number, $k_{\min} = (0.1 - 0.5)k_0$ is the low-frequency wave number cut-off; $R_0(\lambda, \theta; t, s)$ is the power Fresnel reflection coefficient for a smooth water surface, $R_f(\lambda, \theta; t, s; \vec{q})$ is the effective power reflection coefficient for a foam/whitecap/bubbles medium, $\vec{q}$

is a set of the microstructure parameters, and T_0 is the thermodynamic temperature in Kelvin.

According to models (2) - (3) and well known experimental data, the most probable values of the radiometric contrasts observed in the oceans are: ΔT_{Bs} = -5 - +5 K due to surface roughness and ΔT_{Bf} = 10 - 30 K due to foam/whitecap/bubbles (at λ = 0.8 - 8 cm and θ = 0 - 60°). To create a discrete 2-D field of radio brightness, we employ two independent coordinate profiles: $\Delta T_B(X)$ and $\Delta T_B(Y)$. They are modeled by either deterministic or stochastic processes. Fig. 2 demonstrates several typical radiometric profiles, simulated for the ocean surface at different situations. From these data it follows that any combinations or random mixing of the microwave emission fields $\Delta T_{Bs}(x,y)$ and $\Delta T_{Bf}(x,y)$ may produce complex multi-contrast variable textures. Indeed, in a common case, the actual microwave scene, which is $T_B(x,y) = F\{\Delta T_s(x,y); \Delta T_f(x,y)\}$, is computed automatically through some numerical spread operator $F\{...\}$. To reduce uncertainties, we apply a linear operator, which is a weighed sum of the microwave contributions from surface roughness and foam/whitecap, $F\{...\} = \Delta T_s(x,y)\cdot W_s + \Delta T_f(x,y)\cdot W_f$, where $W_{s,f}$ are the corresponding area fractions (dependent on wind speed). Such an approach is suitable for observations with large spatially temporal averaging of radiometric signals. Linear operation allows us to create realistic enough microwave scenes and distinct macro-textures related to high wind situations and foam/whitecap activity [7]. To reduce possible errors arising from computer syntheses, the resulting image $T_B(x,y)$ is filtered by brightness thresholds and certain spatial frequencies.

V. TEXTURE CALLERY

In Fig. 3 we present a gallery of ocean microwave textures, simulated using the different models and radiometric profiles shown in Fig. 2. The values ΔT_B (color bars in Kelvins) are estimated at the wavelength λ = 2 cm. These pictures demonstrate a great variety of ocean microwave textures, depending on the characteristics of the original ocean scene. Deterministic scenes produce periodic (a) and "bombing" (b) textures with distinct features. Such realizations can be matched with high-resolution microwave images of oceanic internal waves and/or solitons. The signatures are revealed in the form of alternating narrow strips with variable brightness and can be perceived as a passive microwave analog of the corresponding radar signatures of internal waves. There are other types of microwave textures such as stochastic, associated with a spatial nonuniformity of surface roughness and variability of the wave number spectrum. Low-contrast extended textures (c) and (d) represent a typical ocean "microwave image background" that has been observed many times in aircraft remote sensing experiments [4,5]. The last example is a complex microwave texture (e), created as a statistical combination of two main factors, surface roughness and foam/whitecap. This is a macro-structure containing a set of bright geometrical spots. It may present a hypothetical microwave picture of a foam-covered ocean surface at high wind conditions.

VI. SUMMARY

In the paper, we reported texture models and simulation techniques related to the ocean surface. The problem is important for advanced passive microwave imagery and applications. In order to provide a comprehensive study, we have explored a number of realistic ocean scenes using deterministic and stochastic methods. Microwave emission contributions have been estimated according to well known theoretical and experimental data. Ocean microwave textures represent a novel class of remote sensing information; they characterize environmental processes and fields through passive microwave pictures. In particular, variable microwave textures can be associated with ocean dynamics, including variations of surface roughness and foam/whitecap coverage. Synthesized complex textures provide the recognition of the relevant signatures. They are revealed in the form of multi-contrast extended and/or localized objects (spots). Experimental verification and adequate analysis of the ocean radiometric signatures is a challenging task for high-resolution passive microwave radiometry.

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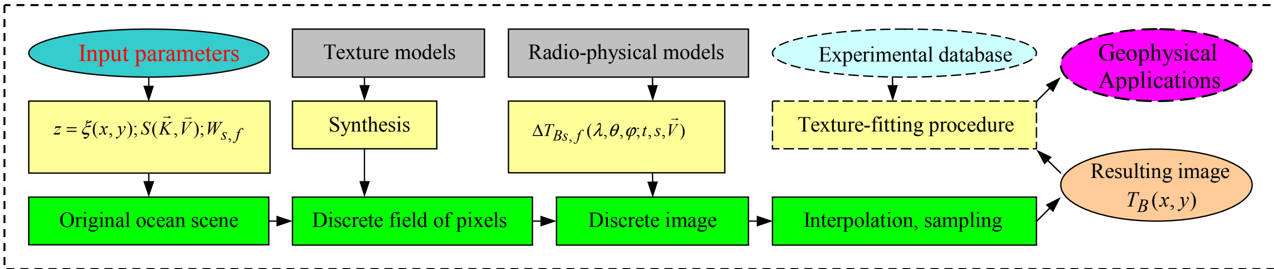

Figure 1. Block diagram of the texture-simulation technique.

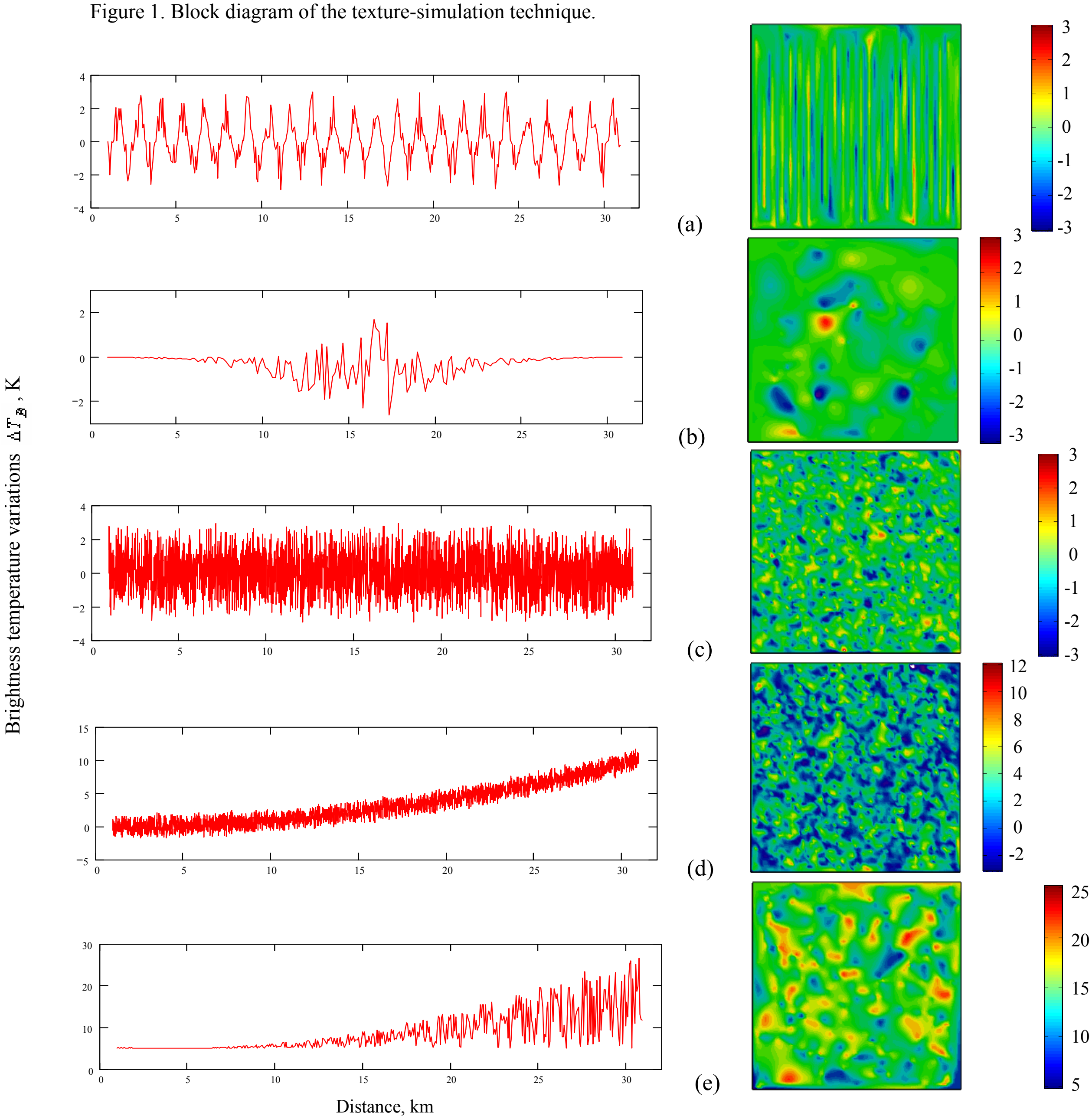

Figure 2 (left). Model microwave radiometric profiles simulated for different ocean conditions. (a) periodic (internal waves); (b) anomaly (soliton); (c) normal stationary random process, (uniform wind); (d) normal process with amplitude trend and constant r.m.s. deviation (nonuniform wind); (e) normal process with amplitude trend and variable r.m.s. deviation (nonuniform increased wind with wave breaking and foam/whitecap).

Figure 3 (right). Computer microwave textures of the ocean surface simulated using the profiles shown in Fig. 2. Test area is 30 km x 30 km. Values of ΔT_B are estimated by (2) - (3) at λ = 2 cm. (a), (b) deterministic models; (c), (d), (e) statistical models (stochastic ocean microwave background).